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Environmental controls and distributions of surface foraminifera from the Otter estuary salt marsh, UK: their potential use as sea level indicators

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Environmental controls and distributions of surface foraminifera from the Otter estuary salt marsh, UK: their potential use as sea level indicators

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Abstract

Fifty-six surface samples were collected from the Otter estuary salt marsh, Devon, UK. Previous work from temperate salt marshes have shown the vertical distribution of foraminifera is primarily controlled by the duration of tidal flooding, whilst working on the general assumption that the elevation of the intertidal zone controls the variations of any environmental parameters affecting foraminifera distributions. Cluster analysis identifies three foraminifera assemblage zones, and a clear vertical distribution of species within the high and low marsh zones is present. However Canonical Correspondence Analysis (CCA) identifies that within the middle marsh elevation has less of a control over the distribution of the dominant *Jadammina macrescens*, whilst pH has increased significance. The calculation of a Root Mean Square Error of Prediction (RMSEP) for the data set indicates an approximate vertical error of $\pm 0.30\text{m}$, which is directly comparable to similar studies in the area. Therefore the foraminifera can be considered suitable indicator proxies for Holocene sea level reconstructions.

Contents

1.0 Introduction	296
2.0 Study location.....	297
3.0 Aims and objectives	298
4.0 Critical literature review	299
4.1 Sea level change	299
4.2 Sea level reconstructions.....	301
4.3 Marshes.....	301
4.4 Foraminifera.....	302
4.5 Foraminiferal zonation	302
4.6 Using foraminifera as sea level indicators	303
4.7 Dead or alive debate.....	303
5.0 Methods for data collection and analysis.....	304
6.0 Results and discussion.....	305
6.1 Transect A	305
6.2 Transect B	306
6.3 Transect C	307
6.4 Transect D	307
6.5 Transect E	308
6.6 Transect F	308
6.7 Ordination of environmental variables and regression analysis	311
7.0 Discussion and analysis	316
8.0 Conclusions.....	319
9.0 Acknowledgments	319
10.0 References.....	319

List of Figures and Tables	Page
Figure 1. Location map of Otter Estuary, Devon, UK	298
Figure 2. Current rate of relative land and sea level change in the British Isles	300
Figure 3. Transect A	306
Figure 4. Transect B	306
Figure 5. Transect C	307
Figure 6. Transect D	307
Figure 7. Transect E	309
Figure 8. Transect F	309
Figure 9. Cluster analysis	310
Figure 10a, b, c. Ordination plots of Canonical Correspondence Analysis	312
Figure 11. Ordination space displaying higher or lower than average optimums	313
Figure 12 a, b, c Canonical Correspondence Analysis ordination plots for the middle marsh zone	314
Table 1. Tide levels at Budleigh Salterton	305
Table 2. Example of typical salinity values	310
Table 3. Species coefficients produced by C^2 analysis	311
Table 4. Axis Statistics	312
Table 5. Higher or lower than average optimums for each species	314
Table 6. Axis statistics	314
Table 7. Overall axis summaries from Canonical Correspondence Analysis	315
Table 8. Statistical parameters of foraminifera training set	316
Table 9. Dominant foraminifera taxa for European salt marshes (Murray, 2000)	317
Table 10. Comparison of RMSEP from researched marshes	318

1.0 Introduction

In this recent age of climate variability, the drive for research and understanding within the field of environmental change has reached an unprecedented level. In particular current concerns regarding global sea level rise associated with anthropogenic warming of the atmosphere and oceans and its impacts on coastal resources have resulted in increased interest in past sea level changes (IPCC, 2007). In order to consider the potential impacts of sea level rise, future scenarios need to be placed within an appropriate geological framework developed from high-resolution reconstructions of late Holocene relative sea level (Gehrels et al., 2006), and this can be achieved through the use of microorganisms, such as foraminifera.

Foraminifera constitute the most diverse group of shelled microorganisms in modern oceans (Sen Gupta, 1999), with the number of extant foraminiferal species estimated to be about 10,000 (Vickerman, 1992). Recently the ecology of foraminifera has become a significant area of study due to the realisation that modern foraminiferal assemblages can provide reliable analogues for understanding past marine environmental changes. According to Sen Gupta (1999) foraminifera are ideally suited to paleoecology because of their significant numerical density in diverse marine sediments, as well as due to their well preserving shells or 'tests'. Benthic foraminifera have colonised all marine environments, from deep oceans trenches to marginal marine habitats (de Rijk, 1995). However it is within salt marsh environments that the mainstay of paleoenvironmental foraminiferal research has been produced. Salt marsh foraminifera are considered to be the most precise biotic indicators for sea level reconstructions and Murray (2006) explained that salt marshes are the best settings for determining past sea levels because they; 1) accrete up to the level of the highest tides; 2) prograde seawards; 3) have an inclined surface with different parts of the marsh related to different tide levels and durations of exposure; and 4) have distinct foraminiferal assemblages. Their suitability to determining past environmental conditions is particularly due to the specific elevation ranges at which these organisms occupy, and when compared with fossil records dated from a core sample the modern day assemblages and fossil indicators can be combined to create sea level reconstructions.

In some cases foraminiferal assemblages provide the potential to relocate former relative sea level to within ± 5 cm (Kemp et al, 2009). However, this degree of precision is not associated with all foraminifera species or assemblages and to allow salt marsh foraminifera to be used as accurate sea level indicators, an understanding of the factors that control their assemblage patterns is needed (Goldstein and Watkins, 1998). Despite foraminifera being used worldwide for sea level reconstructions, their assemblages are not universally uniform. Their distribution is determined by environmental variables including; elevation, salinity, pH, grain size and oxygen availability to name but a few (Murray, 2006). Thus assemblages of foraminifera vary from location to location and this makes it essential for local assemblages to be developed for specific areas (Edwards et al., 2004) with precise and accurate determination of modern species–environment relationships that are representative of the study area (Scott and Medioli, 1986).

The direct influence of elevation with respect to the tidal frame as a control on the distribution of foraminifera, although widely discussed, is not comprehensively clear. Across a saltmarsh site devoid of a simple high–low tide gradient, de Rijk and

Troelstra (1997) found that elevation was at best only comparable to salinity, grain size, and organic matter characteristics for explaining species distributions and abundances. In recent studies it has become apparent that marsh foraminifera are controlled at least as much by their elevation in the tidal frame (as a proxy of tidal flooding) as by mean salinity (e.g., Hayward et al., 2004b). In some areas salinity seems to be the most dominant factor (e.g., de Rijk, 1995). Other studies have also concluded sediment grain size (Matera and Lee, 1972; de Rijk and Troelstra, 1997; Scott et al., 1998), pH (Woodroffe et al., 2005), and organic carbon concentration (de Rijk and Troelstra, 1997) as the major controls on species distributions. Horton (1999), on the other hand, found the relative surface abundances of the agglutinated species *J. macrescens*, *Trochammina inflata* and *Miliammina fusca*, and the calcareous species *Haynesina germanica*, to be tightly constrained by tidal elevation. However it has been suggested that this may be explained by the fact that, at the site in question, grain size, pH, organic matter content, and vegetation cover all exhibited a considerable degree of covariance with tidal elevation.

Southwest England is an area of special interest to sea level studies due to much debate centred on the coastlines true isostatic responses and its effects upon relative sea level. As a result interest in the areas environmental history is high, with various reconstructions having been produced through the use of microorganisms such as foraminifera (Gehrels et al, 2001, Massey et al, 2006). Although there is always a degree of scientific uncertainty surrounding research, what is sure about the southwest region is that it is sinking relative to the sea, making sea level studies within the area of great value. This study is going to build on previous work of foraminifera based sea level studies, and especially the essential need for local assemblages to be developed for specific areas that Edwards et al (2004) describes. Work by Woodroffe et al (2005) Hayward et al (2004), de Rijk and Troelstra (1997), de Rijk (1995), Patterson (1990), and Murray (1971) are particularly linked to this study as the true controls upon foraminiferal assemblages within this particular marsh are established.

2.0 Study location

The salt marsh of the Otter Estuary at Budleigh Salterton is situated on the English Channel on the south coast of England (Figure 1). The marsh area consists of 33.3 ha, and according to the Devon Biodiversity and Geodiversity Action Plan (2004 review); between the 12 estuaries located within Devon the county contains approximately 555 ha of salt marsh in total. The tide levels at Budleigh Salterton are shown in table 1. Flowing due south the lower 2km reach of the River Otter is bounded by sea embankment to the west and sandstone cliff (of up to 10m high) to the east. The estuary broadens to a maximum width of 500m; here the deep, fine alluvium has enabled a well-developed pan and creek system to form. A shingle barrier running eastwards from the west shore virtually closes the estuary from the sea, with the river entering through a 5m gap. Behind the barrier the relatively extensive marsh constitutes a rich diversity of flora and fauna, and has a corresponding variety of bird species.

The salt marsh has no previously published sea level research; and there is great opportunity for further evidential knowledge to be obtained concerning the local

foraminifera assemblages, with the resulting prospect of future relative sea level studies and reconstructions.

A brief history of the area outlines the Otter Estuary as previously being navigable to Otterton until the 15th century, before which it was a valuable commercial resource. Before the estuary silted up creating the salt marshes, the Abbot of the nearby Otterton Priory 'harvested' salt. Historical finds suggest that salt panning in the estuary dates back to roman times and may even go as far back as the Iron Age. The Estuary leads down to the Triassic red cliffs of the East Devon coastline, which forms part of the 95 miles of Jurassic coast – England's first natural World Heritage Site. The coastline was declared as a World Heritage Site by UNESCO in 2001 and includes rocks from the Triassic, Jurassic and Cretaceous periods.

National Grid Reference: SY 073830 Area: 33.3 (ha.) 82.3 (ac.)

Ordnance Survey Sheet 1:50,000: 192 1:10,000: SY 08 SE

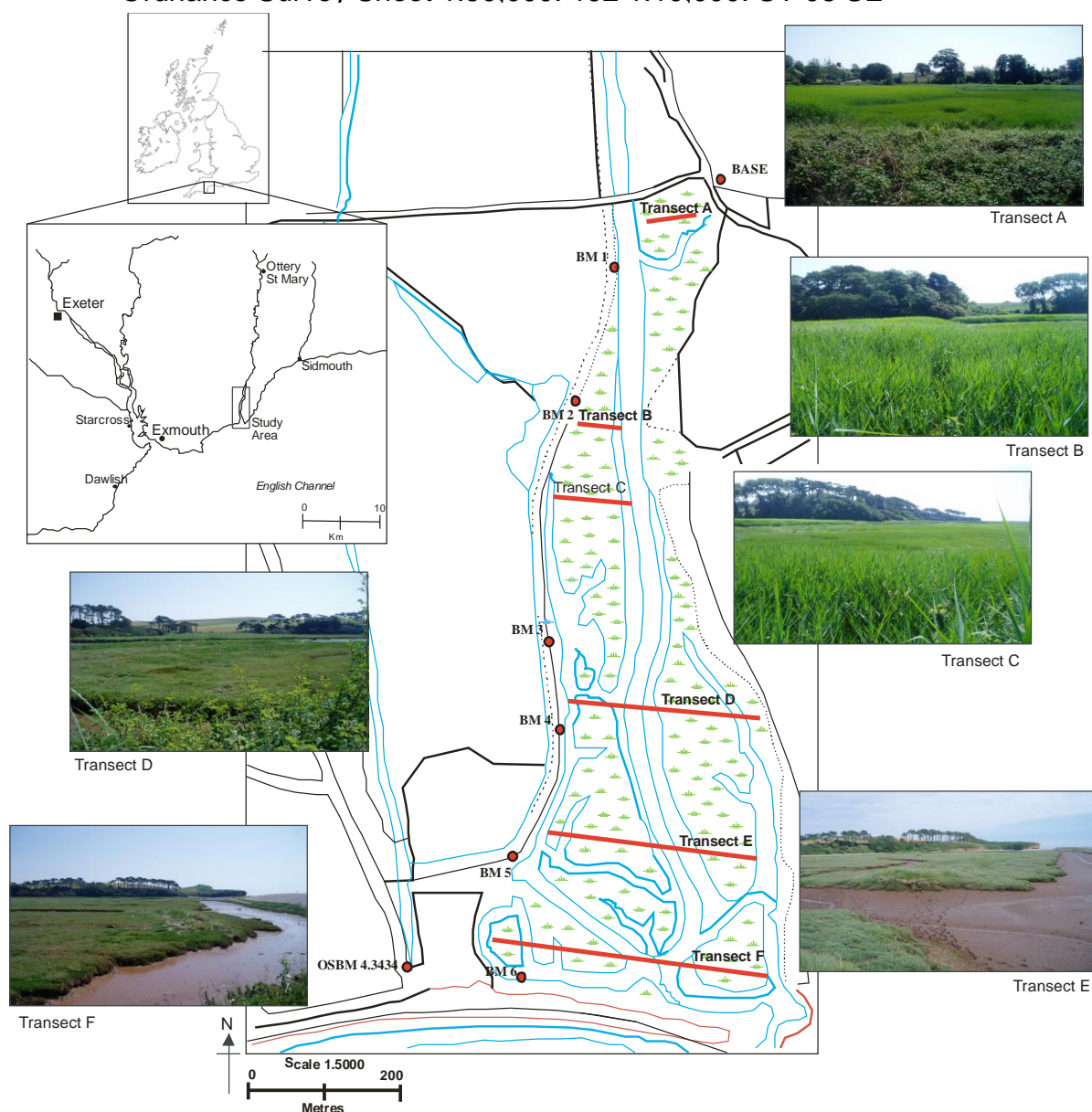


Figure 1: Location map of Otter Estuary, Devon, UK

3.0 Aims and objectives

Due to the abundance and the formation of well preservable shells, foraminifera are very useful in analysing recent and ancient marine environments (Murray 2002). The aim of this ecological study is to identify the different modern day foraminifera species from surface samples and to prove the relationship between the biota and the environment. Unlike other studies whereby results are based on a single transect, using multiple transects will better identify any spatial differences across the marsh.

4.0 Critical literature review

4.1 Sea level change

The continuing rise of global sea level is currently one of the most important issues facing today's society. What makes it so vitally important to humanity is its potential to alter ecosystems and habitability in coastal regions, where an ever increasing percentage of the population lives (Douglas, 2001). General consensus is that the rate of global average sea level rise over the 20th century is 1.5mm/yr, and the projected global sea level rise from 1990-2100 is predicted at 0.11-0.77m (Intergovernmental Panel on Climate Change, 2001). Since the last glacial maximum, 20,000 years ago sea level has risen up to 130m in some locations and the global average sea level has risen 0.5mm/yr over the past 6000 years.

IPCC scientist estimates that there is a 50% chance that widespread ice sheet loss may no longer be avoided because of the greenhouse gasses currently in the atmosphere and the heat within the planets water. Due to the thermal properties of water the ocean stores 1000 times more heat than the atmosphere. Therefore even if greenhouse gas emissions were completely stopped from now on, sea levels would continue to rise well into the next century, due to the stored heat and long lag time (IPCC 2007). Therefore upping the importance of relative sea level studies further. It is Adam (2007) who states that it is not the processes that are of doubt; it is the timescales that are affected by uncertainties.

Sea level change has varying rates and impacts across the planet. The ice movements throughout the UK associated with the last ice age resulted in complex isostatic responses which are, as of yet, not fully understood (Shennan et al., 2002). Hayworth (1982) emphasises the point that changes in sea level due to the last deglaciation are not globally uniform, but instead happen at different rates on a regional scale. Analysis by Shennan and Horton (2002) of more than 1200 radiocarbon dated samples that constrain relative sea levels in Great Britain over the past 16000 years provided initial estimates of current land level changes. Their findings displayed maximum relative uplift occurring in central and western Scotland (1.6mm yr⁻¹) and maximum subsidence in southwest England (1.2mm yr⁻¹). Therefore implying that the southwest coastline concerned within this study would be expected to have experienced relative sea level rise above that of the average around the coast of Britain throughout the 20th century.

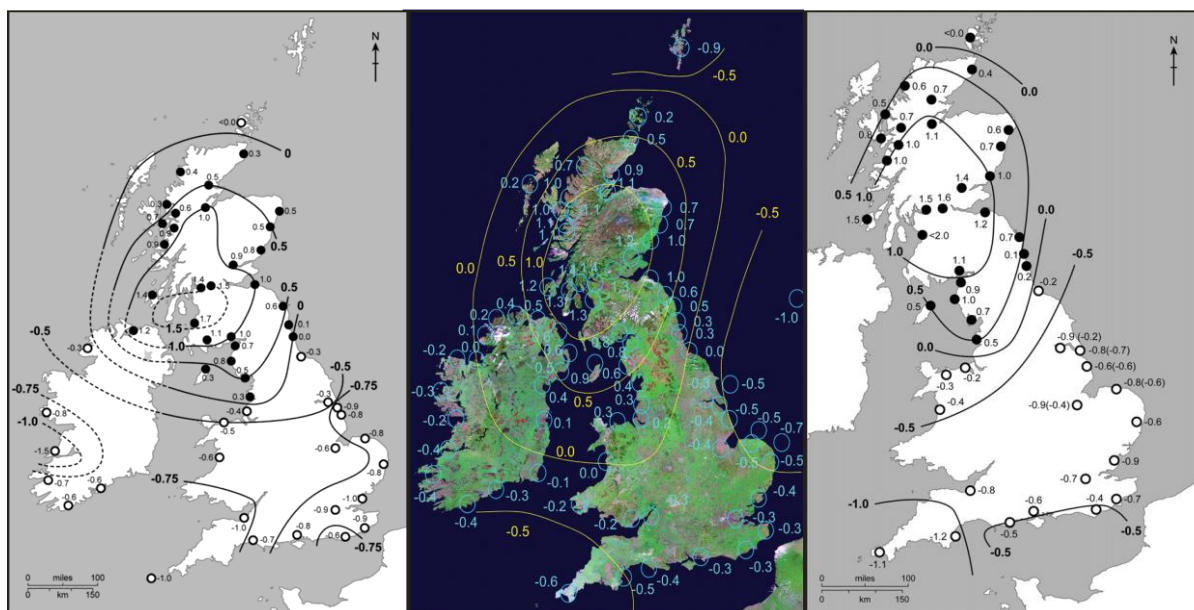


Figure 2: Current rate of relative land and sea level change in the British Isles in mm. Left to right; Gehrels (2010), Shennan et al (2009), and Shennan and Horton (2002).

However since Shennan and Horton's 2002 publication there have been questions regarding the published data's correctness. Initially Gehrels (2006) raised his concerns on the quality and quantity of the data points which were used in the study and undertakes detailed analysis of four of the data points which were located in Devon and Cornwall. When compared with geophysical models he concluded that the isostatic rate of change for southwest England has been over estimated by Shennan and Horton. Shennan later adds that it should be understood that the combination of contrasting relative sea level changes around the British Isles and a large database of paleo-sea level reconstructions provides a rigorous test for quantitative Glacio-Isostatic Adjustment (GIA) models. The GIA models offer a spatial picture not easily inferred from field research at individual sites, and notifies two studies demonstrating the recent advances: Brooks et al. (2008) and Shennan et al. (2006). Their model predictions show good agreement with the majority of the geological evidence of relative sea level change since 16 ka B.P., but unlike Shennan and Horton (2002), they did not include a map summarizing current rates. However recently both Shennan et al (2009) and Gehrels (2010) have since produced new estimations with accompanying maps summarising what they believe to be the true isostatic rates of uplift and subsidence around the UK.

The map produced by Shennan et al (2009) shows considerable differences to the one produced seven years earlier by Shennan and Horton (2002). The 2002 map displays a greater relative uplift occurring in Scotland and a greater relative subsidence in southwest England. Shennan et al (2009) attribute these differences to (1) the availability of more data to test models; (2) model improvements; (3) calculating late Holocene rates for the past 1 ka instead of 4 ka; and (4) greater consideration of sediment consolidation. In contrast Gehrels (2010) extracts land-motion data for the UK from Shennan and Horton (2002) and produces a new map which takes into account the regional 20th century sea level rise (~0.14m) for the past 100 years as well as the processes of ocean syphoning (-0.3mm/yr). A consideration for a possible long-term late Holocene ice-equivalent sea level rise of 0.1 ± 0.1 mm/yr

is also included within the findings. The key results for southern Britain from this study show the relative subsidence for the southwest coastline to have been overestimated, while the figures for the southeast coastline were underestimated.

4.2 Sea level reconstructions

Gehrels et al (2001) signifies the importance of creating a contemporary sample for sea level reconstructions using microscopic organisms, such as foraminifera. Patterson et al (2000) states that it is the specific elevation ranges at which these organisms occupy that is the key to determining the past conditions. Combined with fossil records dated from a core sample and after the precise heights in the contemporary sample are known to a specific degree of accuracy, the modern day and fossil indicators can be combined to create sea level reconstructions. However some studies (de Rijk, 1995; Hayward et al., 2004b) have indicated that elevation is sometime not the key determinant in the organisation of foraminiferal species assemblages. Thus signifying the importance of thorough research concerning the distribution of modern assemblages in regards to environmental variables as a first step before sea level reconstructions are attempted from fossil data.

Gehrels et al (2001) does state that there is now an advance in the accuracy and precision of results gained due to the change from qualitative to quantitative methods of analysis. Computer programs now allow researchers to take advantage of multiple regression, classification and ordination techniques as well as transfer functions to improve the accuracy of their results (Gehrels 2000; Gehrels et al 2001; Zong 1998 and Zong and Horton 1999).

4.3 Marshes

Salt marsh can be considered a wider category of tidal marsh (Diaber 1986) and as Manning (2003) describes their environments are within the intertidal zone and are characterised by the presence of fine sediments and halophytic vegetation. Adam (1990) stresses the point that the flooding waters are saline. Murray (2006) explains how marshes form in low energy areas sheltered from wave attack. He then proceeds on to state how extensive marshes are a feature of accretionary shorelines such as deltas, estuaries and lagoons. Marshes are highly dynamic environments that accrete and prograde but are also subject to localised erosion from waves and currents. Salt marshes are found on low energy coasts in temperate and high latitudes, while in the subtropics and tropics salt marsh environments are replaced by mangrove communities. European marshes tend not to be as organic rich when compared to those in North America (Edwards, 2001) and are essentially confined to the uppermost intertidal zone, unlike in North America where they often extend into the lower intertidal zone.

The macro environment of a given salt marsh may seem uniform, but a variety of habitats are available to smaller organisms (Teal, 1996). Bradshaw (1968) suggested that the following factors are beneficial to foraminifera living in marsh habitats: (a) lowering of temperature in the shade provided by larger and smaller marsh vegetation such as grass, algal mats, and algal clumps; (b) protection from desiccation provided by algal cover; and (c) the availability of food in the form of diatoms and other algae. Furthermore Hayward and Hollis (1994) state there is actually no reliable evidence that a particular kind of marsh grass would support a particular kind of foraminiferal assemblage.

4.4 Foraminifera

Foraminifera are marine organisms that live in a range of saline habitats (Bell et al. 1992). They are well suited to salt marsh environments because they are well adapted to low pH and a wide range of salinity values. The majorities of foraminifera are benthic and live in the surface of sediment, being classified as epifaunal. Some specimens are infaunal and live below the surface being able to reach deeper levels through the aid of bioturbation, where downwards movements of water and plant roots allow the foraminifera to move deeper through the sediment. However there are only some species that are adept to living in these conditions (Saffert et al, 1998). Infaunal foraminifera species tend to be common along low-latitude coasts and are normally only found in cores from the middle and lower zones of the salt marsh (Gehrels 2002).

Salt marsh foraminifera are predominantly agglutinated species. Their walls consisting of microscopic detrital sedimentary grains which are held together with organic glue (Murray et al. 1989). Also when viewed under a light microscope are seen to be beige in colour. Foraminifera often have somewhat clumped distributions due to the nature of micro-environments and their reproductive needs (Murray, 1991), with assemblages in a sample normally consisting of 1-2 dominant species, 2-3 subsidiary species and any number of rare species. Dead assemblages normally have greater species richness, with Murray (2003) concluding that it is probably because they are the result of an accumulation over time. Murray (2003) progresses on to state that the size of foraminifera roughly coincides with their age, with the average growth rate being around 30 to 40 μm a month for about 4 months, although it does vary between species. Most species seem to show a number of reproductive phases throughout the year. For example *Nonion depressulus* has been recognised as having 8 or 9 breeding periods a year (Murray et al. 1983), and in the Exe estuary the biomass of the foraminifera increases from March to May and again from September to November (Murray et al. 1991).

4.5 Foraminiferal zonation

A suite of widespread agglutinated taxa is generally regarded as typical of coastal salt marshes (Phleger, 1970, Murray, 1971, Phleger, 1977). It includes *Ammonium salsum*, *Arenoparrella mexicana*, *Jadammina macrescens*, *Miliammina fusca*, *Trochammina orchacea*, and *Trochammina inflata*. Careful examinations of the distributions of these and other marsh species of foraminifera reveal that low marsh assemblages can be distinguished from high marsh ones on the basis of species dominance. Murray (2006) concludes that the ecological controls on marsh foraminifera are controlled by different factors depending upon location.

In environments where limited mixing of saltwater and freshwater occurs, the duration and frequency of tidal submergence is the dominant influence on the assemblage. Scott and Medioli (1980) explain how species present change in accordance to elevation up the marsh between mean sea level and the highest tide. In environments where considerable mixing of saltwater and freshwater is occurring, salinity tends to govern the distribution of species, due to varying levels of tolerance (Johnson and Patterson 1992). De Rijk (1995) explains how changes in pore-water salinity can also affect the foraminiferal distribution. He found that salinity was the controlling factor within the marsh, which in turn was controlled by seepage of fresh groundwater, and the infiltration of sea water and rainfall. De Rijk found that marshes

sloping towards the sea were controlled by tidal influence. However marshes with complex morphologies, such as creeks and pools, often altered the foraminiferal distribution. Murray (2006) also mentions how shade from vegetation or leaf litter, effects of drying, and pH can also have an impact on assemblage to a lesser extent.

4.6 Using foraminifera as sea level indicators

The use of ecological information from dead organisms and their interrelationship with the past physical environment, other animals and plants, is known as paleoecology. Paleoecology employs uniformitarianism, which is based on the theory in which the factors that affect abundance and distribution of living organisms (such as foraminifera) in the past are the same as those that effect living organisms in the present (Summerfield, 1991).

Salt marshes are ideal for core sample analysis of these marine fossils due to the intertidal zonation and its ability to keep pace with the rate of moderate sea level change. Rodwell (1990) states that there are three main zones located within a typical salt marsh: low marsh zone; middle marsh zone and high marsh zone. According to Gehrels (1994) these three zones can be divided up floristically rendering to plant communities, tolerance to tidal inundation and interspecific competition. Furthermore Adam (1990) concludes that there is also a variation in micro-flora and fauna with elevation, but goes on to state that this is best observed in vascular plants. As a result of these floristic zonations, each species of foraminifera can be found at specific heights (Scott et al. 1996) of a tidal frame, and thus have an indicative meaning, and changes in the foraminifera stratigraphy make it possible to reconstruct the height of the marsh surface relative to sea level. However this technique cannot be used for all floras found on the salt marsh as small numbers of species occur in varying abundances in a wide variety of combinations (Rodwell 1990). Regression equations are used to calculate the relationship between height and the contemporary foraminiferal assemblage. The equations create a transfer function, which are used for palaeo-estimates for ecological relationships (Dale and Dale 2002). Furthermore to this, predictions of future variations in sea levels can be constructed (Gehrels et al. 2003), as well as assessing the effect of past environmental events (eg earthquakes) on the sea (Hayward et al. 2004) and how dominant ocean currents and water movements have developed over time (Jennings et al. 2004).

As well as foraminifera, other marine organisms such as diatoms and testate amoebae can be used to similar effect. Gehrels (2001) for example used a multi proxy approach to obtain a more accurate measurement of sea level change. However the identification of diatom taxa considered to be more complex and is thus more time consuming. On a final note a relatively new application of foraminifera is in investigations of seismically induced coastal land movements (e.g. Scott 2001, Shennan et al. 1996, 1998, 1999).

4.7 Dead or alive debate

Debate exists as whether to use the living, dead or total assemblages of foraminifera. It has been suggested that total (live plus dead) surface foraminiferal populations most accurately reflect modern environmental conditions and should be employed in paleoenvironmental reconstructions (Scott and Medioli, 1980a). However, the composition of the live training set is dependent on the surface

conditions at the time of collection, and is therefore composed of foraminifera which are best suited to the prevailing environmental parameters (temperature, salinity, pH) at the time of sampling. The live population will therefore vary over the course of the year dependent on these changing conditions and is likely to differ considerably from the dead foraminiferal population (Horton, 1999), making the live training set of little use for paleoecological reconstructions (Murray, 2000).

5.0 Methods for data collection and analysis

The sampling strategy was used to establish the overall pattern of foraminiferal assemblages across the marsh and their relation to tide levels (elevation) (Shennan et al 1996), salinity and pH. Six suitable transects were chosen to sample low, middle and high marsh ecologic zones and to the transverse microfossil communities creating an environmental gradient. This differs from the majority other studies in which one transect is chosen transverse each zone, rather than multiple transects. Tide timetables were consulted to determine the best time to collect samples from the lower tidal zone and along the transect differences in elevation were measured with a surveying level (which are accurate to within 1cm) and leveled to Ordnance Datum.

The sample stations were located at marked changes in the topography and vegetation of the marsh. A standardised sediment volume of 10 cm³ (10 cm² by 1 cm thick) was taken for analysis. This volume coincides with studies by (Horton et al, 1998 and De Rijk, 1995). At each sample site conductivity (salinity) and pH levels were also measured. The pH was measured using a standard pH probe. First the probe was placed in a buffer solution (pH 7), and then set using a pink (pH 4) solution to calibrate it. A 1:2.5 (soil: water) solution was stirred up and then gently mixed for 2 minutes until the probe reader settled before the reading was recorded. Salinity was measured using a conductivity probe. A 1:2.5 (soil: water) solution was stirred up, whilst keeping the probe covered, and then gently mixed for 2 minutes or until reader settled. A measure of Conductivity in either $\mu\text{S}/\text{cm}$ or mS/cm was taken, along with temperature ($^{\circ}\text{C}$) and then later converted into salinity values (ppt).

Once the samples had been collected they were then transported to the lab where they were placed in a buffered ethanol solution with Rose Bengal stain and allowed to soak for 24-48 hours, which will allowed the living forams to be identified (Walton 1952). After this they were wet sieved between 63 μm and 500 μm , the material collected in the 63 μm sieve was washed and once this had settled, any suspended organic material was able to be decanted. Finally a sample splitter was used to split the sample eight ways because it is important to identify the foraminifera from a sample that is conveniently small in size to avoid a very long count process. The remaining organic material was then spread onto a counting tray and studied using a binocular microscope. Any foraminifera found were placed on a slide to be counted and identified. Any living organisms were also noted, these were identified by the pink staining from the rose Bengal.

A Microscope of 40-80X magnification was used to analyse the counting tray for foraminifera, and once foraminifera were found, the area around was cleared of organic matter and carefully picked out with a fine paintbrush and placed on a labeled micro faunal slide. Foraminifera were identified and separated accordingly

depending on species variation. The key used to identify the foraminifera species, is commonly used to identify intertidal species found in the British Isles salt marshes and ones also found in North American salt marshes (Gehrels, 2002).

6.0 Results and discussion

Table 1: Tide levels at Budleigh Salterton relative to ordnance datum. Data from Admiralty Tide Tables (2010).

Tide Level	Height (m OD)
Highest Astronomical tide	4.8
Mean High Water of Springs	4.6
Mean High Water of Neaps	3.4
Mean Sea Level	0.8
Mean Low Water of Neaps	1.7
Mean Low Water of Springs	0.5

A total of 56 surface samples were collected along the gradients of 6 transects, with 9 different foraminifera taxa being identified. However the total count for *Eggerella scabra* was only 2, with it been found to only occur in 1 sample (F10). In the analysis diagrams, only dead foraminifera are considered as the distribution of live species is not considered a valid modern analogue for paleoenvironmental studies (Murray, 2000). The number of live species in samples was relatively low, especially in the higher and middle marsh zones.

Figures 3-7: Percentages of foraminifera along the six transects. a) *Phragmites australis*; b) *Juncus geradi*; c) *Spartina maritima*; d) *Puccinella maritima*; e) *Atriplex portulacoides*; f) *Red fuscue*; g) *Triglochin maritima*; h) *Mudflat*.

6.1 Transect A

Transect A (figure 3) had a gradual declining gradient spanning 37m across the higher marsh zone. It traversed two different vegetation zonations of *Phragmites australis* and *Juncus geradi*, and had a total relief of 0.38m. A total of 4 foraminifera taxa were found from the 9 sample sites, in decreasing order of maximum abundance these four species were: *Miliammina fusca* (mean value and range: 47%, 6-75%), *Haplophragmoides Wilberti* (30%, 0-47%), *Jadammina macrescens* (16%, 6-44%) and *Trochammina inflata* (6%, 0-50%). Total numbers of foraminifera for this transect were lower than all others due to its location in the high marsh on the limits of the high tide. However counts of at least 150 were able to be obtained and these were deemed acceptable.

The pH levels remained relatively constant along the transect with all readings (except one) between values of 6.27 and 6.65, which is often considered about average for the high marsh. The anomaly lies at the far end of the transect (A9), here the pH is much higher at 7.33. Salinity readings are also fairly regulated along the entire transect, with levels remaining low and never reaching above 4.3ppt. The reading of sample A9 is again of particular interest because of its low reading; however this can probably be explained by its close proximity the large freshwater channel.

6.2 Transect B

By far the shortest at just 22m, transect B (figure 4) has a total relief of just 0.12m and is again located within the higher marsh zone, amongst a heavily vegetated area of *Phragmites australis*. Just 4 samples were taken along this transect with the same 4 taxa, and the same order of dominance as identified from the previous transect (A). Their mean values and ranges were also closely matched; *Miliammina fusca* (49% 13-87%), *Haplophragmoides Wilbert* (30%, 3-60%), *Jadammina macrescens* (14%, 9-20%) and *Trochammina inflata* (9%, 0-18%). Even though this transect was still within the high marsh and the *Phragmites australis* reeds, the counts were a lot higher than transect A, with minimum counts of 200 being easily reached.

The pH readings for the transect are 6.74, 6.87, 7.03 and 7.54. The salinity levels increase with distance from the freshwater channel, but the highest they reach is 3.5ppt at the furthest point.

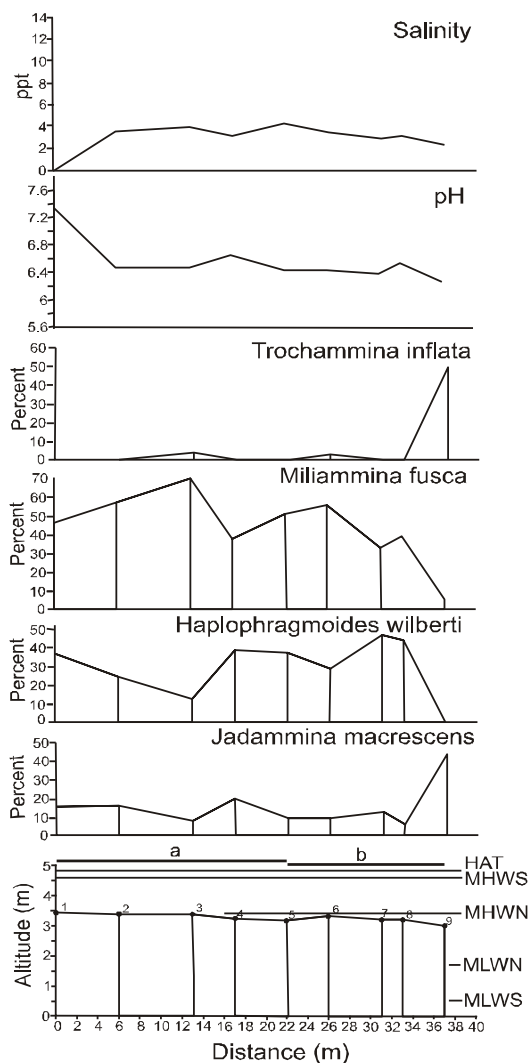


Figure 3: Transect A

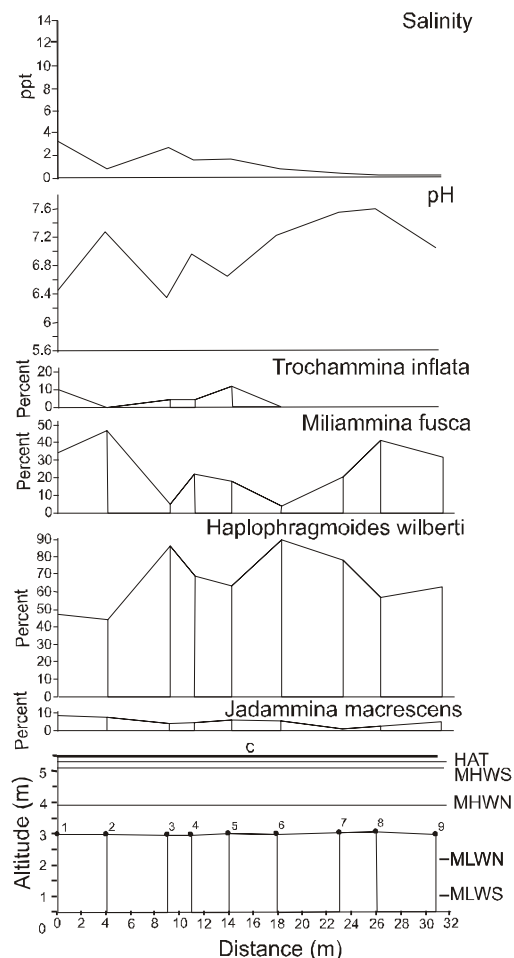


Figure 4: Transect B

6.3 Transect C

Transect C (figure 5) traverses 31m of the upper section of the middle marsh, where the vegetation is completely dominated by *Spartina maritima*. The transect is relatively level with a total relief of 0.10m, however points along this transect are up to 0.97m lower than those experience in transect A. The same 4 taxa are again present however the mean value for *Haplophragmoides wilberti* more than doubles to 66%, and with this it replaces *Miliammina fusca* as the dominant species, which drops to 25%. *Jadammina macrescens* and *Trochammina inflata* still have little presence throughout with mean values of just 5% and 3% respectively. Levels of pH again remain relatively constant with slight fluctuations, and salinity corresponds strongly with the readings from transect B with a highest value of 3.3ppt.

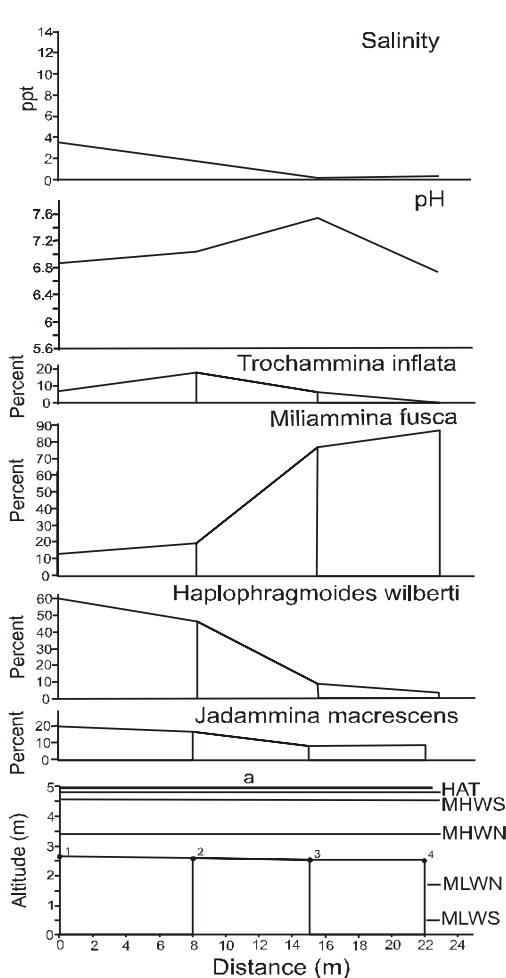


Figure 5: Transect C

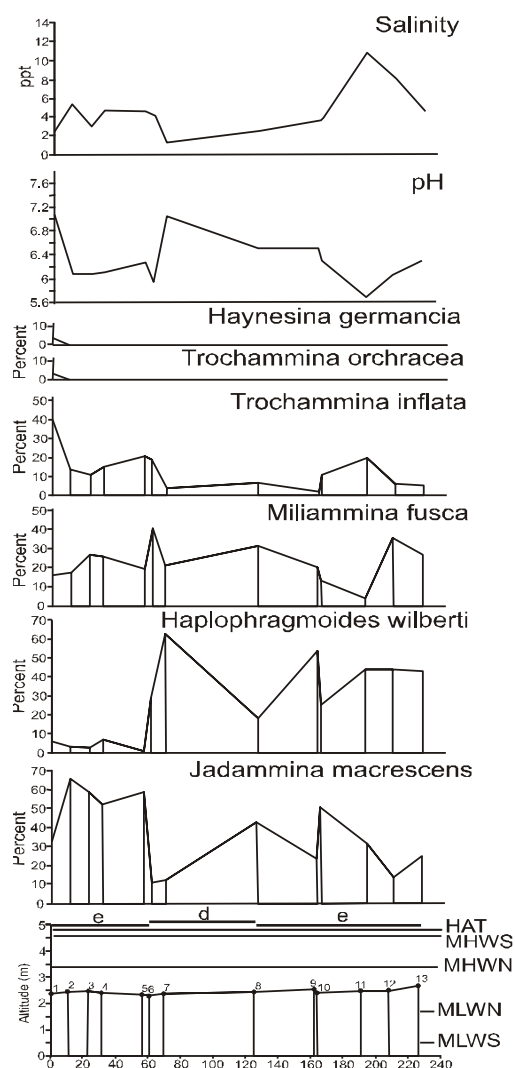


Figure 6: Transect D

6.4 Transect D

Transect D (figure 6) straddles either side of the main estuary channel within the middle marsh zone. A total of 13 samples are taken along the 226m transect which experiences *Puccinellia maritima* and *Atriplex portulacoides* vegetation commonly

associated with the middle marsh zone. The total relief of the transect is 0.35m however it does not have a continual gradient due to it spanning numerous mid-marsh channels. With this transect and the firm transition into the middle marsh zone the foraminiferal assemblages have a significant change. A total of 6 foraminifera taxa were found, in decreasing order of maximum abundance these 6 species are: *Jadammina macrescens* (40%, 11-66%), *Haplophragmoides wilberti* (26%, 1-63%), *Miliammina fusca* (23%, 4-41%), *Trochammina inflata* (14%, 2-40%). *Trochammina ochracea* and *Haynesina germanica* both appear in D1, with only a couple of counts each.

Levels of pH along this transect are predominantly lower than the previous ones located higher up the marsh. It has a pH range of 5.69-7.06, and the lowest readings for the entire marsh are recorded at D6 (5.92) and D11 (5.69). Salinity on average progresses to a slightly higher level along the transect, especially high readings are present at D11 (10.8ppt) and D12 (8.1ppt).

6.5 Transect E

Traversing 286m of the middle-low marsh zone, a greater number of vegetation species are experienced (see figure 7). *Red fescue*, *Atriplex portulacoides*, *Puccinellia maritima*, *Triglochin maritima* as well as the mudflat are all encountered. A total of 7 foraminifera taxa were identified, in decreasing order of maximum abundance the nine species are: *Jadammina macrescens* (56%, 11-96%), *Trochammina inflata* (16%, 4-38%), *Miliammina fusca* (14%, 0-45%), *Elphidium williamsoni* (6%, 0-61%), *Haplophragmoides wilberti* (4%, 0-37%), and *Cibicides lobatulus* (2%, 0-19%). Only 4 counts *Haynesina germanica* were found from E6 (mudflat). In contrast to the rest of the transect which is dominated by agglutinated species, Sample E6 (mudflat) is dominated by the two calcareous species *Elphidium williamsoni* and *Cibicides lobatulus*.

The pH values for this transect are a series of fluctuations, with the exception of E5 which drops to a low level of 5.81. Salinity levels throughout remain at a slightly higher level than the high marsh zones. However two extremes do occur at E1 and E5 where the recorded levels are significantly lower and higher respectively, than the rest of the transect.

6.6 Transect F

Located on the seaward edge of the marsh, behind the 10m high barrier, this transect is 347m long in total (figure 8). Traversing the zone of widely populated *Atriplex portulacoides* vegetation, the transect spans numerous channels of varying size. The transect possesses the greatest elevation difference with a high of 2.49m and a low of 1.71. The foraminiferal assemblages found are the most diverse experienced on the marsh with 9 different taxa being identified. However the finds of *Eggerella scabra* and *Trochammina ochracea* were only present in one sample each, both with an insignificant presence. The remaining 7 taxa found were, in decreasing order of maximum abundance: *Jadammina macrescens* (62%, 4-90%), *Trochammina inflata* (13%, 0-39%), *Elphidium williamsoni* (8%, 0-61%), *Cibicides lobatulus* (6%, 0-32%), *Miliammina fusca* (4%, 0-18%), *Haplophragmoides wilberti* (3%, 0-7%), *Haynesina germanica* (3%, 0-27%).

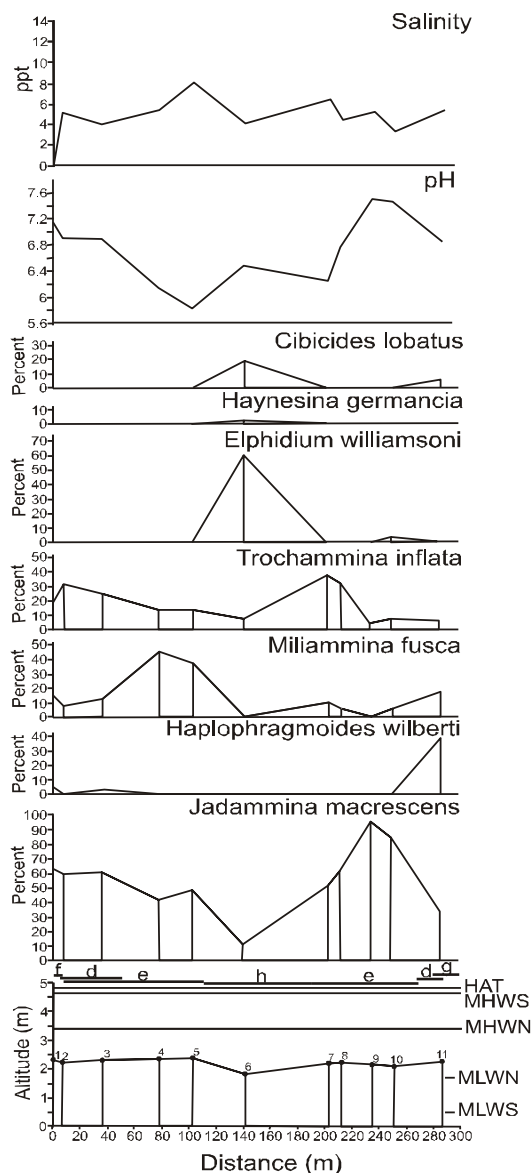


Figure 7: Transect E

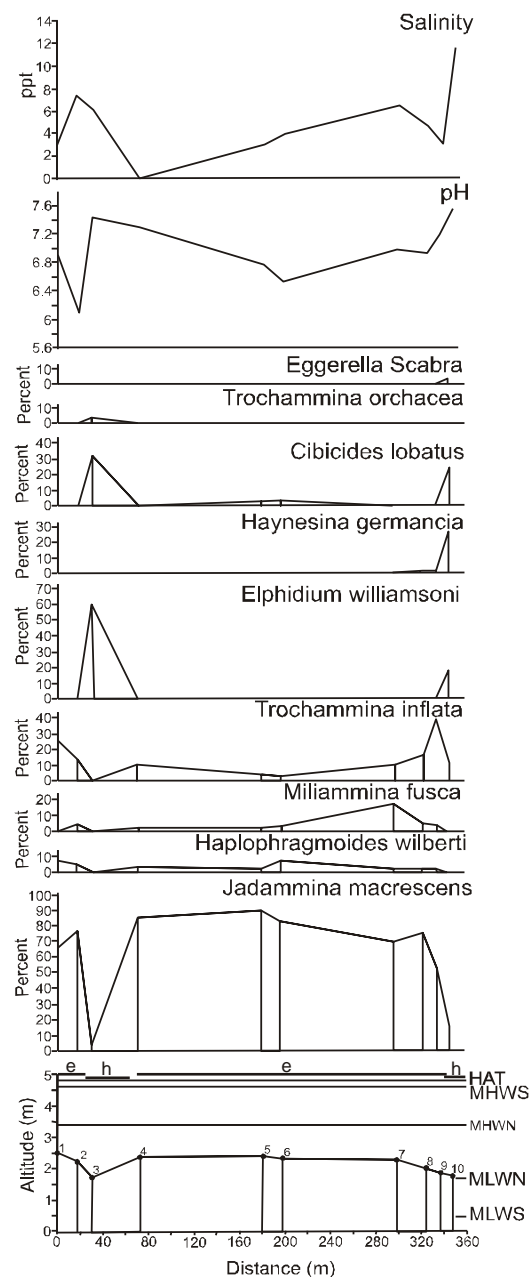


Figure 8: Transect F

Compared to the rest of the marsh covered by this study's research, the pH levels for this transect are comparably high >6.5 (excluding F2). The salinity values observed (table 2) are on a comparable high with transect E, however there is a greater variance in fluctuations and the highest salinity level of 11.7ppt being recorded at F10.

Table 2: Examples of Typical salinity values (ppt). Data from www.njmssc.org/education/lesson_plans/Salinity_Lab_Booklet.pdf

Body of Water	Typical Salinity
A Salty lake (Red Sea)	36-50 ppt
The Ocean	30-35 ppt
Mouth of estuary by a river	1-15 ppt
Mouth of estuary by the ocean	15-30 ppt
Tidal fresh river	0.5-14 ppt
Freshwater stream or river	<1 ppt

Across the marsh the salinity and pH measurements were variable. Salinity values were often low due to the numerous freshwater channels spanning the marsh. Values ranged from 0.1 to 11.7 ppt, with slightly higher values being found in the lower marsh. The pH across the marsh ranged from 5.69 to 7.58; with the lowest values along transect D in the middle marsh.

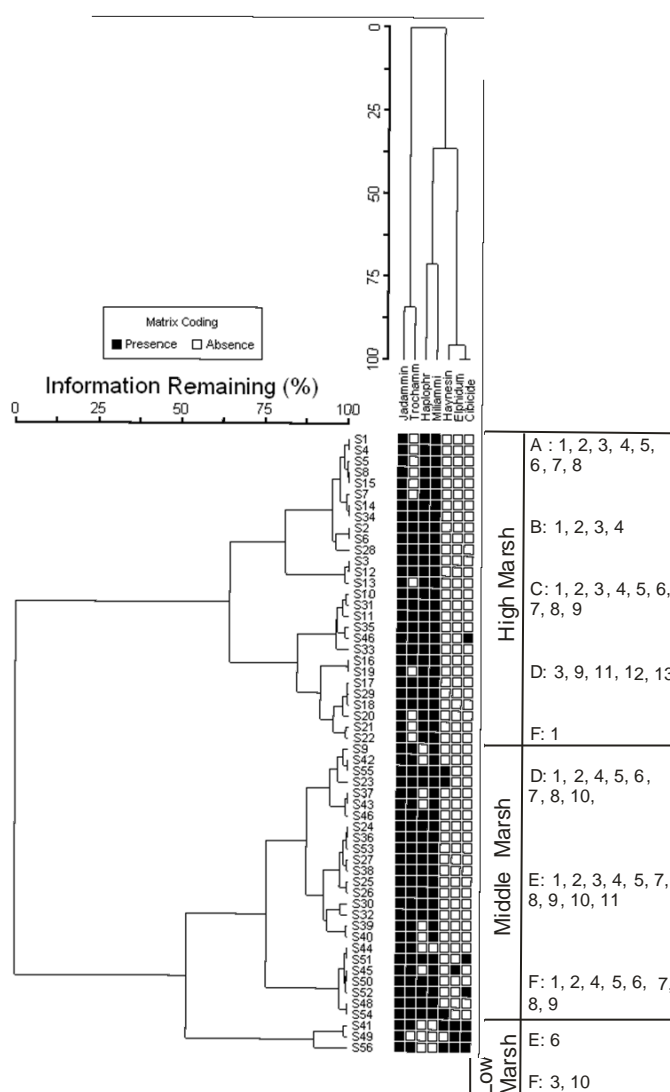


Figure 9: Cluster analysis revealing three assemblage zones

95% of the marsh is dominated by the 4 agglutinated foraminifera taxa, in descending order of maximum abundance these were; *Jadammina macrescens* (35%), *Haplophragmoides wilberti* (25%), *Miliammina fusca* (24%) and *Trochammina inflata* (11%). The calcareous species *Elphidium williamsoni*, *Cibicides lobatulus* and *Haynesina germanica* dominate the mudflats. When plotted against elevation and using cluster analysis (figure 9), three foraminiferal zones can be identified. Zone 1 is dominated by *Haplophragmoides wilberti* and *Miliammina fusca* and it corresponds with the high marsh zone determined by vegetation, especially *Phragmites australis*. Zone 2 is dominated by *Jadammina macrescens* and the calcareous species *Elphidium williamsoni*, *Cibicides lobatulus* and *Haynesina germanica* occur in Zone 3. The latter three species are absent from Zone 1, and de Rijk (1995) suggests that this is due to the low pH of pore water (around 6.5) in the upper marsh. Scott (1976b) and Goldstein (1988) note that within the subtropical marshes this is not the case and calcareous species are also abundant on the high marsh, and are even preserved in Holocene marsh deposits.

Table 3: Species coefficients produced by C² analysis. Dead foraminifera in 56 surface samples. N.-number of occurrences. Max % - maximum relative abundance. Optimum – optimum height at which species is found. Tolerance – standard deviation range.

Species	N	Max %	Optimum (m above OD)	Tolerance (m)
<i>Jadammina macrescens</i>	56	96	2.37	0.29
<i>Haplophragmoides wilberti</i>	45	90	2.63	0.33
<i>Miliammina fusca</i>	53	87	2.71	0.41
<i>Trochammina inflata</i>	44	50	2.34	0.29
<i>Elphidium williamsoni</i>	4	61	1.77	0.09
<i>Cibicides lobatulus</i>	6	32	1.83	0.22
<i>Haynesina germanica</i>	5	27	1.83	0.28
<i>Trochammina orchacea</i>	2	3	2.03	0.45
<i>Eggerella scabra</i>	1	3	1.77	0.30

6.7 Ordination of environmental variables and regression analysis

Once the foraminifera have been identified it is now common practice for computer analysis to be used to indicate their meaning. Canonical Correspondence Analysis (CCA) is an ordination method developed by ter Braak that uses a multivariate direct gradient analysis, which is an advanced form of Correspondence Analysis (CA). CCA shows both patterns of assemblage composition and relationship between species and each of the environmental variables (Kent and Coker 1992). Thus it will display the extent to which elevation, salinity and pH are controls on the distribution of the foraminifera. It is a preferred program to use than other ordination methods such as CA and Detrended Correspondence Analysis (DCA) in this type of research because it has been tailored to specifically include environmental data (Maddy and Brew 1995). The relative strength and direction each of environmental variables is correlated to the length and direction of its line on the CCA plot.

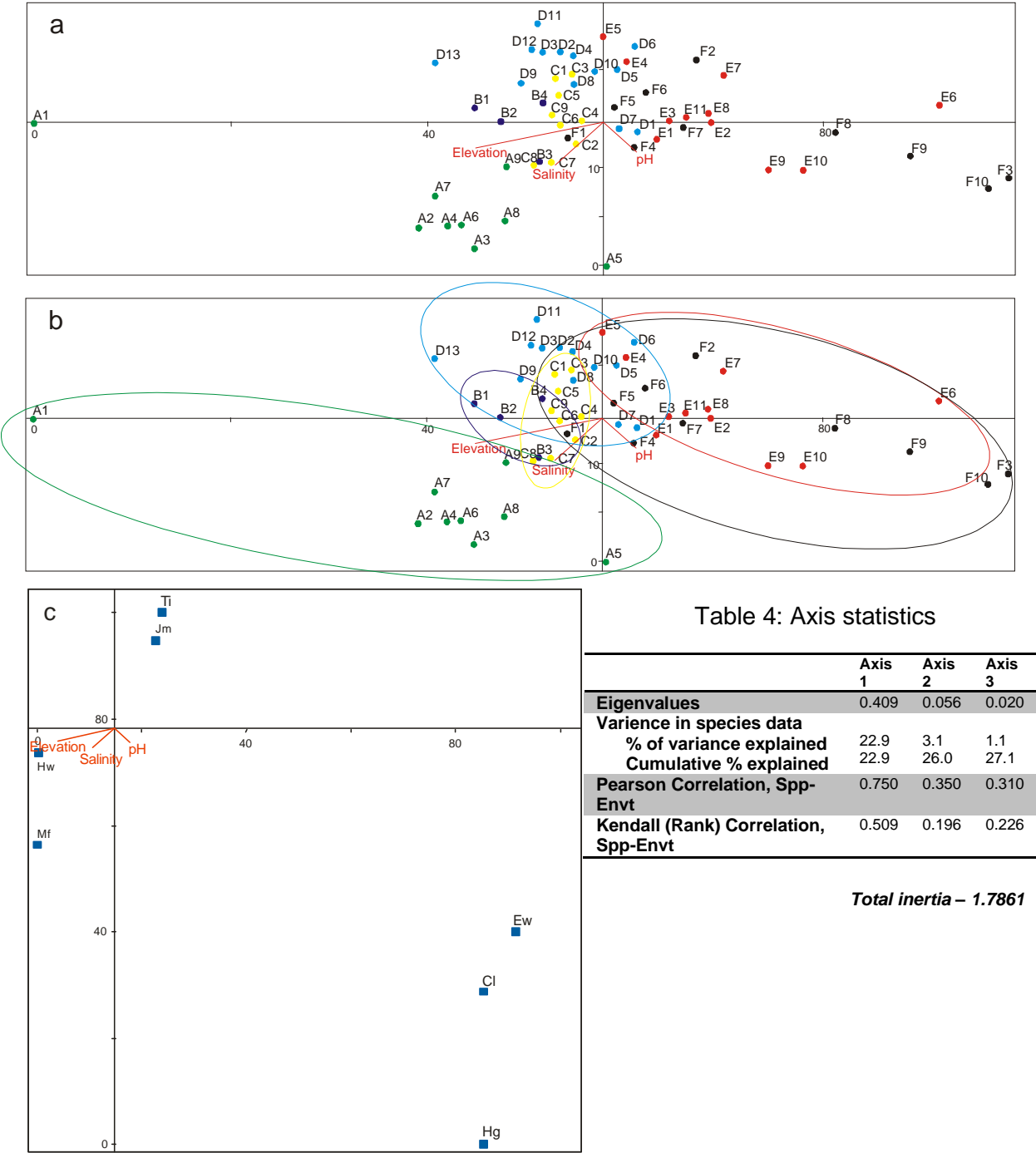


Figure 10: Ordination plots of Canonical Correspondence Analysis results for a) 56 samples, b) samples showing grouped transects and c) seven most important species. Jm – *Jadammina macrescens*; Ti – *Trochammina inflata*; Hw – *Haplophragmoides wilberti*; Mf – *Miliammina fusca*; Ew – *Elphidium williamsoni*; Cl – *Cibicides lobatulus*; Hg – *Haynesina germanica*

The CCA was used to extract the synthetic gradients for the Otter estuary salt marsh. These gradients were the basis for illustrating the different niches of foraminifera taxa via ordination diagrams. Table 4 displays that the first eigenvalue is fairly high, implying that the first axis represents a fairly strong gradient. The second axis is much weaker, and the third weaker still. Sample locations indicate their compositional similarity to each other and Figure 10.b highlights this. Samples tend to be dominated by the species that projected toward them in the ordination space and figures 10.b and 10.c can be used to demonstrate this. On the species bio-plot *Haplophragmoides wilberti* and *Miliammina fusca* are situated close to one another displaying a strong correlation between the two species, and reinforcing the results of the cluster analysis which suggested the species were often found together in the high marsh. Further evidence for this is that when samples belonging to the same transect are grouped together in the ordination space (Figure 10.b) *Haplophragmoides wilberti* falls within the space covered by all three high marsh transects A (green), B (purple) and C (yellow). While *Miliammina fusca* is within transect A and is close to B and C. The middle marsh species *Jadammina macrescens* and *Trochammina inflata* are situated close to one another and fit within the parameters of transects D, E and F, shown by the blue, black and red ellipses respectively. The calcareous species are shown to be correlated with transects E and F, with *Elphidium williamsoni* and *Cibicides lobatulus* placed within both transects and *Haynesina germanica* on the cusp of transect F.

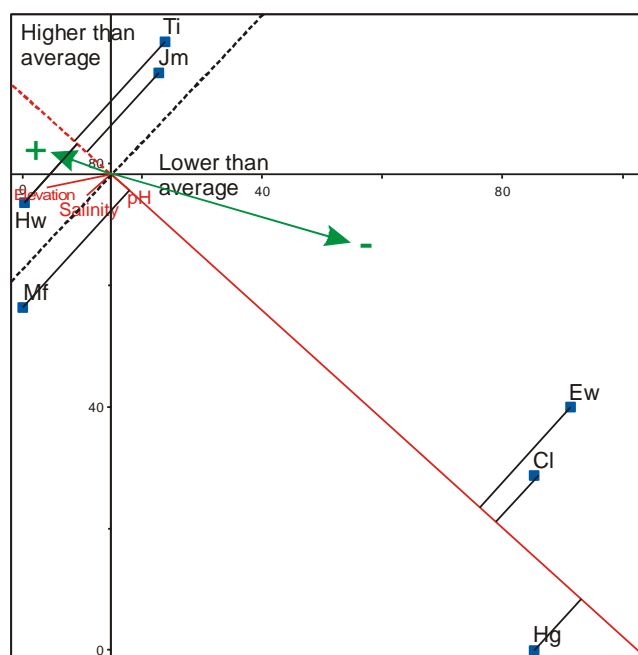


Figure 11: Ordination space displaying higher or lower than average optimum for species against pH and positive and negative correlations

Using the length of the environmental vectors to indicate its importance to the ordination, confirms that elevation has the greatest influence upon species distribution. Using perpendiculars drawn from the species to environmental arrow gives an approximate ranking of species response to the particular variable, and whether the species has a higher or lower than average optimum on that environmental variable (see table 5). The green arrows in Figure 11 can also be

used to distinguish whether a species has a positive or negative relationship with an environmental variable.

Table 5: Higher or lower than average optimums for each species

	Jm	Hw	Mf	Ti	Ew	Cl	Hg
Elevation	Lower	Higher	Higher	Lower	Higher	Higher	Higher
Salinity	Higher	Lower	Lower	Higher	Higher	Higher	Lower
pH	Higher	Higher	Lower	Higher	Lower	Lower	Higher

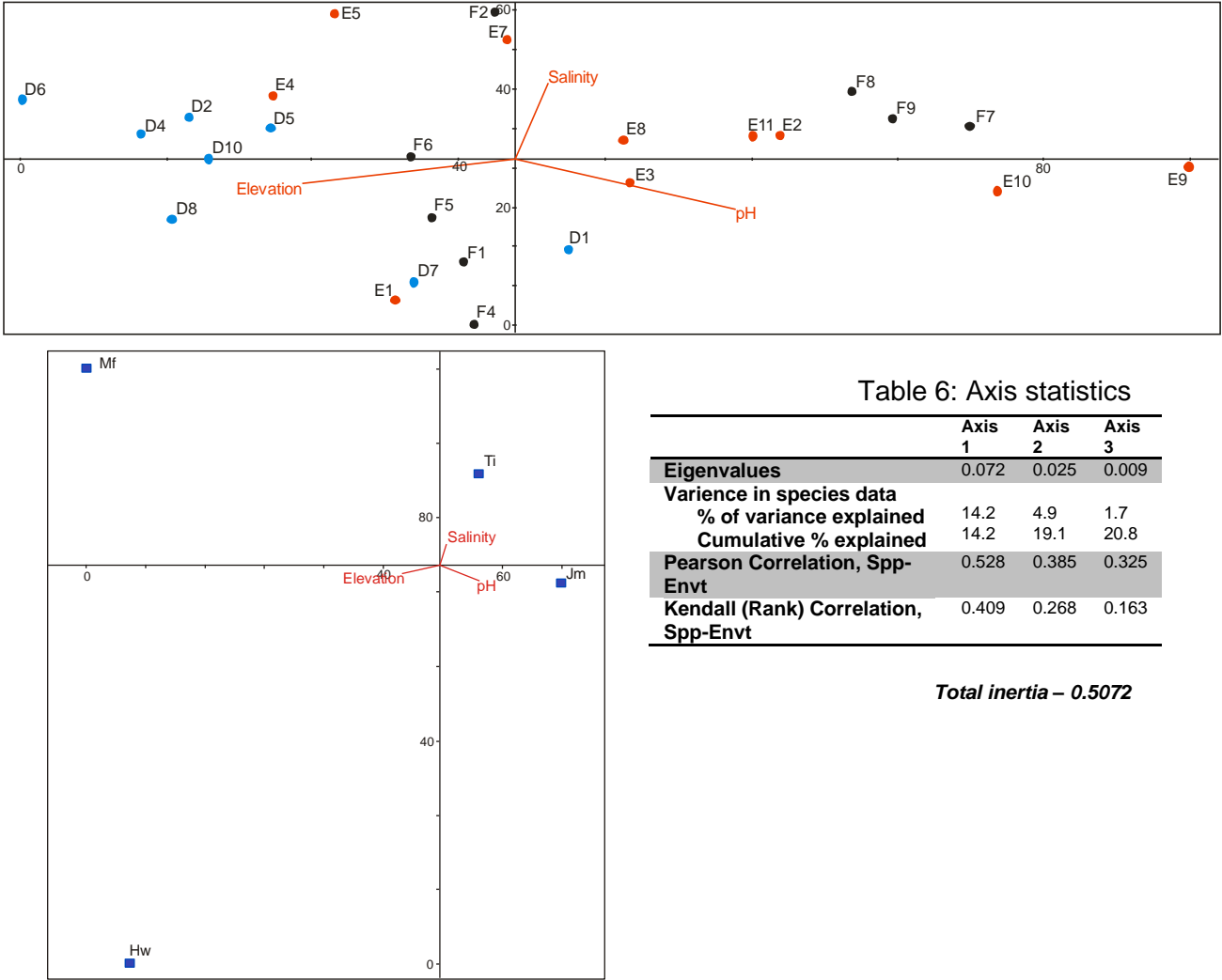


Table 6: Axis statistics

	Axis 1	Axis 2	Axis 3
Eigenvalues	0.072	0.025	0.009
Variance in species data			
% of variance explained	14.2	4.9	1.7
Cumulative % explained	14.2	19.1	20.8
Pearson Correlation, Spp-Envt	0.528	0.385	0.325
Kendall (Rank) Correlation, Spp-Envt	0.409	0.268	0.163

Total inertia – 0.5072

Figures 12a and 12b: CCA ordination plots for the middle marsh zone, as identified by the cluster analysis.

Within the middle marsh zone (2) the environmental variable with the greatest effect upon species distribution is less clear than in the high and low marsh where elevation is the dominant key to the distribution of species assemblages. Elevation is shown to have a higher than average optimum and positive correlation for the high and low species. However this is not the case for *Jadammina macrescens* and *Trochammina inflata*. In a new CCA ordination where just the sample for the middle marsh are considered (Figure 12) *Jadammina macrescens* and *Trochammina inflata* still appear to be closely correlated in the ordination space, However in this zone *Haplophragmoides wilberti* and *Miliammina fusca* are not. Positions of samples

belonging to the same transect do not have the same degree of similarity in the middle marsh zone. According to the ordination, in this zone pH possess a much stronger hold over the distribution of species assemblages. The eigenvalues can be seen to be much lower for each axis (Table 6) than previously (Table 4), with them only explaining 20.8% of the total variance. They are still in the same numerical order, again implying that the first axis represents the strongest gradient with the second axis and third axis being weaker. However axis 1 experiences a significant decline and the differences between them have narrowed, resulting in the overall significance of the three environmental variables declining. On the other hand the percentage of variance explained suffers a decrease for both elevation and salinity, however for pH an increase occurs. This confirms that pH in this middle marsh zone has a greater control over the distribution of species than it does in the higher and low marsh areas. An axis statistics summary can be displayed for three scenarios of CCA. When samples from; 1) the whole marsh; 2) only the middle marsh (as identified by cluster analysis) and; 3) only the low plus high marsh are considered, results display that the measured environmental variables have the most effect in low and high marsh areas, with total variance standing at 42.2%. This compared to the middle marsh which has 20.8%. Studies of a similar nature often experience higher figures for total variance, such as Siccha et al (2009) where the cumulative percentage of explained variance in species data is 79.2%.

Table 7: Axis summaries from CCA results from ordinations of samples collected from; the whole marsh (56 samples), middle marsh (26), and low + high marsh (27)

	Whole marsh			Middle marsh			Low & high marsh		
	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
Eigenvalues	0.409	0.056	0.020	0.072	0.025	0.009	0.576	0.079	0.031
Variance in species data									
% of variance explained	22.9	3.1	1.1	14.2	4.9	1.7	35.5	4.9	1.9
Cumulative % explained	22.9	26.0	27.2	14.2	19.1	20.8	35.5	40.3	42.2
Pearson Correlation, Spp-Envt	0.750	0.350	0.310	0.528	0.385	0.325	0.830	0.583	0.370
Kendall (Rank) Correlation, Spp-Ent	0.509	0.196	0.226	0.409	0.268	0.163	0.214	0.490	0.292

The software programme C² was used to assess the relationship between foraminifera, elevation, pH and salinity. Weighted Averaging Partial Least Squares (WA-PLS) regression and the Modern Analogue Technique (MAT) were used as statistical tools. The regression statistics produced by the software included the coefficient of determination (r^2), the Root Mean Square Error of the training set (RMSE) and the maximum bias (the difference between the mean observed and the predicted values). The Root Mean Squared Error of Prediction (RMSEP) was the calculated through the cross-validation process, known as 'jack-knifing'. This is when each surface sample is eliminated in turn and the rest of the training set was used to calculate its elevation (Birks, 1995). RMSEP reflects the precision set for the height calculation based on a fossil foraminiferal assemblage, and Gehrels (2000) identifies this as a useful parameter when foraminifera are used as sea level indicators. The choice of component is usually based on which gives the lowest RMSEP value under cross validation. MAT produces the lowest RMSEP values however it has been criticised for being over optimistic when assessing errors (Telford and Birks, 2005), and a larger data set would possible be needed. This training set included 56 samples and the number of analogues to which a sample is compared must be

critically examined. For this data set the number of possible analogues was set at 10, however a similar study by Southall et al (2006) set it at 5 for their 31 samples. When a high residual value appears, such as in the case of salinity, it means the training set was unable to predict the true elevation of the sample.

Table 8: Statistical parameters of foraminifera training set

	R ²	RMSE (m)	R ² (jack)	RMSEP (m)	Max bias (jack) (m)
Elevation (WA-PLS)	0.4576	0.2862	0.3973	0.3023	0.7110
pH (WA-PLS)	0.0824	0.4720	0.0064	0.5011	0.9432
Salinity (WA-PLS)	0.1838	1459.0	0.0720	1580.6	4236.8
Elevation (WMAT)	0.5329	0.2688	0.5093	0.2747	0.8222
pH (WMAT)	0.0323	0.5056	0.0283	0.5054	0.7472
Salinity (WMAT)	0.1917	1524.5	0.1689	1563.8	4088.0

RMSE-root mean squared error, r^2 -coefficient of determination, RMSEP-root mean squared error of prediction, r^2 (jack)- coefficient of determination of the jack-knifing cross-validation, Max bias (jack)-maximum bias of the jack-knifing cross-validation, W-PLS – Partial least squared Weighted Averaging regression, WMAT-Weighted Modern Analogue Technique. WA regressions are based on inverse de-shrinking methods (Birks, 1995; Juggins, 2003).

7.0 Discussion and analysis

The foraminifera species found in the Otter estuary salt marsh are all considered cosmopolitan species. Table 9 shows the distribution of marsh taxa in Europe (Murray, 2006). Of the species identified in this study, *Jadammina macrescens*, *Miliammina fusca*, *Trochammina inflata*, *Elphidium williamsoni* and *Haynesina germanica* are all shown to dominate marshes in England. *Haplophragmoides wilberti* is shown to be a subsidiary species. Only *Cibicides lobatulus*, *Eggerella scabra* and *Trochammina ochracea* are not present in the table 9. However appearances of the latter in UK salt marshes is not uncommon, e.g. Massey (2006). Murray (2006) explains how *Cibicides lobatulus* and *Eggerella scabra* are more commonly associated with the deeper waters of shelf environments. The appearance of *Cibicides lobatulus* and *Eggerella scabra* within sample F10 coincides with this due to the location of the sample site, which was the closest to the sea by the tidal inlet. However there are examples of both species being found within UK salt marshes. Edwards and Horton (2000) notify the identification of *Eggerella scabra* within a saltmarsh on the Arne peninsular, Poole harbour. *Cibicides lobatulus* is found in the Erme Estuary and Frogmore Creek, both locally located to this study with Devon (Massey, 2006).

High latitude salt marshes commonly have the presence of three or four zones and the canonical correspondence analysis displays three on this particular marsh. Conformation of this can be seen in figure 10.b where the samples appear in clusters when plotted in ordination space. However the zones are not as clearly defined as in some other studies such as Gehrels and Newman (2004), especially within the middle marsh zone, although the larger data set and the greater tidal range should be taken into consideration. For temperate salt marshes such as this one, Jennings et al. (1995) assume that elevation of the intertidal zone controls variations in salinity, pH and vegetation.

Table 9: Dominant foraminifera taxa for European salt marshes, Murray (2006).

Approximate latitude, °N	60–58	57	54	53	55–51	45	43	45	38
Tides	None	None	None	Mes.	Mes.–mac.	Mes.	Mac.	None	None
Salinity	Br.	Br.	Br.	Br.–mar.	Br.–mar.	Br.	Br.	Br.	Br.
Geographic area	S Scandinavia	Denmark	Germany	Netherlands	England	France	N Spain	Italy	Greece
<i>Ammonium salsum</i>	M		**				M	M	
<i>Balticammina pseudomacrescens</i>									
<i>Haplophragmoides wilberti</i> + sp.									
<i>Jadammina macrescens</i>								M	
<i>Miliammina fusca</i>				M			M		
<i>Tiphotrecha comprimata</i>				M					
<i>Trochammina inflata</i>									
<i>Reophax moniliformis</i>					M				
<i>Polysaccammina ipohalina</i>									
Small miliolids									
<i>Ammonia</i> group									
<i>Elphidium albumbilicatum</i>									
<i>Elphidium williamsoni</i>									
<i>Haynesina germanica</i>	M								
<i>Elphidium excavatum</i>									
<i>Elphidium</i> sp.									
<i>Fissurina lucida</i>					M				
<i>Aubignyna hamblensis</i>									
<i>Helenina anderseni</i>									
<i>Discorinopsis aguayoi</i>									M
<i>Elphidium translucens</i>									

In this study, the environmental variables in the ordination appear to be correlated, inferring that the measured variables (elevation, salinity, pH) all primarily depend upon the frequency of tidal flooding. This therefore supporting the suggestions of Jennings et al (1995). However when CCA is performed for only the samples extracted from the middle marsh, the correlation between variables decreases.

The species that are primarily controlled by height are *Haplophragmoides wilberti* and *Miliammina fusca*. Only *Jadammina macrescens* and *Trochammina inflata* show a negative correlation with elevation. These two species which dominate the middle marsh have a higher than average optimum for salinity and pH, thus coinciding with the correlation figures shown in table 5. Results from the CCA, where only the samples taken from the middle marsh zone are considered, suggests that within the middle marsh the foraminiferal assemblages are not as clearly defined by elevation. Within the middle marsh zone the morphology is more complex than the higher and lower marsh zones. The high and low marsh zones both consist of a more simple high to low, gently sloping gradient towards the sea, unlike the middle marsh zone with its complex of channels and creeks which proves to be less uniform. This could significantly contribute to a considerable mixing of saltwater and freshwater occurring, and as Johnson and Patterson (1992) identify this can result in salinity governing the distribution of species, due to varying levels of tolerance. This would correspond with de Rijk's (1995) study which found that the foraminiferal assemblages of some salt marshes in Massachusetts, USA were governed by salinity. However to establish whether this truly is the case a sampling strategy which encompassed a much larger time frame would need to be used, this would enable the full seasonal and fortnightly variability of salinity to be captured. Plus according to the CCA results displayed in figure 11, it is not salinity that appears to have the increased affect upon distribution within the middle marsh, it is in fact pH. De Rijk (1995) signifies that *Jadammina macrescens* shows the ability to adapt to various conditions and to occupy any environment fast. It is even found in environments outside the salt marsh proper such as in Cape Cod Bay and on the continental shelf (Phelger and Walton, 1950; Culver and Buzas, 1981a). *Trochammina inflata* has

previously been noted not to be sensitive to flooding frequency, salinity, substrate, vegetation or food source. However Matera and Lee (1972) described a correlation with grain size distribution. The resourcefulness of these two species, especially *Jadammina macrescens*, could explain as to why they dominate the middle marsh areas.

The foraminiferal assemblages of the Otter estuary salt marsh possess the vertical zonation that is commonly found when species dominance is analysed. In the higher and lower marsh zones the assemblages of foraminifera are clearly constrained by elevation and would certainly be suitable proxy for use for sea level reconstructions. However the assemblages within the middle marsh zone where *Jadammina macrescens* dominates, elevation does not possess such a stranglehold over distribution. Within this zone the environmental control upon distribution is not as clear cut, with salinity and especially pH having more of an influence most likely due to the complex nature of the middle marsh. Salt marshes with a vertical zonation such as this one can still differ in their dimensions and foraminiferal assemblages (Jennings and Nelson, 1992). Thus making a study involving surface samples to analyse the use of foraminifera as sea level indicators a certain prerequisite. However the study must cover all modern environments which may be recorded within salt marsh cores. The need for a more time based approach is also prevalent to ensure variability's, especially regarding seasons, are covered.

Although already confirmed, an applicable global model for paleoenvironmental reconstructions based on salt marsh foraminifera is not possible, due to salt marshes possessing their own characteristics which affect the distribution of foraminifera species assemblages. This particular salt marsh does have an acceptable fit. When the RSEMP (using elevation as the environmental parameter) from this study is compared to the findings of various other studies, it can be seen that due to the higher tidal range the value is significantly higher than most. However when compared to the data for the southwest UK the WA-PLS produced RMSEPs are extremely closely matched. For elevation a figure of 0.3023 directly compared to Massey et al's (2006) value of 0.29m. The WMAT produced RMSEP is even lower at 0.2747.

Table 10: Comparison of RMSEP from researched marshes. Source: Southall et al. (2006)

Site	N	Model	RMSEP (m)	Mean tidal rang (M)	RMSEP/ tidal range (%)	Reference
Catlins coast, New Zealand	31	WA-Tol	0.05	1.50	3.1	Southall et al. (2006)
Maine, USA (average of 4 locations)	68	WA-PLS	0.25	3.11	7.9	Gehrels (2000)
Southwest United Kingdom (average of 2 locations)	85	WA-PLS	0.29	3.45	8.3	Massey et al. (2006)
Western Denmark	16	WA-Tol	0.16	1.50	10.7	Gehrels and Newman (2004)
Connecticut, USA (average of 4 locations)	91	WA-PLS	0.18	1.36	13.5	Edwards et al. (2004)
Nova Scotia, Canada	46	WA-Tol	0.06	1.50	3.7	Gehrels et al. (2005)

A low RMSEP implies that sea level changes can be precisely reconstructed from fossil foraminifera preserved in salt marsh sediments. N-number of samples in training set. WA-Tol-tolerance down-weighted Weighted Averaging regression, WA-PLS-Weighted Averaging Partial Least Squares regression (Birks, 1995).

8.0 Conclusions

The surface samples of foraminifera distribution from the high and low marsh areas of the Otter estuary are strongly related to tidal elevation. The middle marsh distribution where *Jadammina macrescens* dominates strongly has a much weaker correlation with elevation, and pH becomes more of a determinant. Considering the marsh as a whole, elevation is the primary control upon the distribution of the foraminiferal assemblages. The RMSEP result ($\pm 0.30\text{m}$) provides the approximate vertical error for the indicative meaning, and it directly compares to Massey et al (2006) results ($\pm 0.29\text{m}$) which were taken from two Devon salt marshes. This study therefore confirms the usefulness of salt marsh foraminifera from the Otter estuary as sea level indicators.

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10.0 References

- Admiralty Tide Tables, 2010, Volume 1, United Kingdom and Ireland (Including European channel ports). United Kingdom Hydrographic Office. Annual.
- Adam, P. 1990. Saltmarsh Ecology. Cambridge, Cambridge University Press
- Birks, B. 1996. Chapter 6: Quantitative paleoenvironmental reconstructions. In: Maddy, D, and Brew, J.S. eds. Statistical modeling of quaternary science data. Technical guide. Vol 5, Quaternary research association. Cambridge. 161-254
- Bradshaw, J.S. 1957. Environmental parameters and marsh foraminifera. *Limnology and Oceanography*, 13: 26-38
- Bradshaw, 1968 J.S. Bradshaw, Environmental parameters and marsh foraminifera, *Limnology Oceanography* 13 (1968), pp. 26–38
- Culver, S.J. and Buzas, M.A. 1981a. Recent benthic foraminiferal provinces on the Atlantic continental margin of North America. *Journal of Foraminiferal Research*. 11: 217-240
- Dale, A.L. and Dale, B. 2002. Application of ecologically based statistical treatments to micropaleontology. In: Haslett, S.K., ed. *Quaternary Environmental Micropalaeontology*. Arnold, London. 259-286
- De Rijk, S. 1995b. Salinity control on the distribution of salt marsh foraminifera (Great Marshes, Massachusetts). *Journal of Foraminiferal Research*. 25: 156-166

De Rijk, S. and Troelstra, S. 1997. Salt marsh foraminifera from the Great marshes, Massachusetts: environmental controls. *Paleoceanograph, paleoclimatology, paleoecology*. 30 (1-4): 81-112

Douglas, 2001 B.C. Douglas, Sea Level Change in the era of the recording tide gauge. In: B.C. Douglas, M.S. Kearney and S.P. Leatherman, Editors, *Sea Level Rise; History and consequences*, Academic Press, San Diego (2001), pp. 37–64

Ebenay, J.P. and Guillou, J.J. 2002. Ecological transitions indicated by foraminiferal assemblages in paralic environments. *Estuaries*. 25: 1107-1120

Edwards, R.J. and Horton, B.P. 2000. Reconstruction relative sea-level change using UK salt-marsh foraminifera. *Marine Geology*. 169 (1-2): 41-56

Edwards, R.J. 2001. Mid-to-late Holocene relative sea-level change in Poole Harbour, Southern England. *Journal of Quaternary Science*, 16: 221-235

Edwards, R. J., Wright, A.J., Van de Plassche, O. 2004. Surface distributions of salt-marsh foraminifera from Connecticut, USA: modern analogues for high- resolution sea level studies. *Marine micropaleontology*. 51 (1-2): 1-21

Gehrels, W.R. 1994 Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, USA. *Journal of Coastal Research* 10: 990-1009

Gehrels, W.R. 2000. Using foraminiferal transfer functions to produce high-resolution sea level records from salt marsh deposits, Maine, USA. *Holocene* 10: 367-376

Gehrels, W.R. 2001. Discussion of: Nunn, Patrick D., 1998. Sea-Level Changes over the Past 1,000 Years in the Pacific. *Journal of Coastal Research*. 14(1): 23-30. *Journal of Coastal Research*. 17: 244-245

Gehrels, W.R. 2002. Intertidal foraminifera as paleoenvironmental indicators in: Haslett, S.K. (Ed.), *Quaternary Environmental micropaleontology*. Arnold Publishers

Gehrels, W.R. 2006. Sea-level rise and coastal subsidence in southwest England. *Reports and Transactions of the Devonshire Association*. 138: 25-42

Gehrels, W.R. 2010. Late Holocene land- and sea-level changes in the British Isles: implications for future sea level predictions. *Quaternary Review*. xxx: 1-13

Gehrels, W.R., Roe, H.M., & Charman, D.J. 2001. Foraminifera, testate amoebae and diatoms as sea-level indicators in UK saltmarshes: a quantitative multi-proxy approach. *Journal of Quaternary Science* 16: 201-220

Gehrels, W.R., Van de Plassche, O., van der Schrier, G., Weber, S.L. and Wright, A.J. 2003. Sea-level variability in the northwest Atlantic during the past 1500 years: a delayed response to solar forcing? *Geophysical Research Letters*. 30: 1921, doi. 10.1029/2003GL017558.

Gehrels, W.R., Szkornik, K., Bartholdy, J., Kirby, Sarah, J., Bradley, L., Marshall, W., Heinemeier, J., Jørn B., and Pedersen, T. 2006. Late Holocene sea-level changes and isostasy in western Denmark. *Quaternary Research*, 66, (2): 288-302

Goldstein, S.T. 1999. Foraminifera: a biological overview. In Sen Gupta, B.K., ed. *Modern foraminifera*. Dordrecht: Kluwer. Pp 7-55

Goldstein, S.T. and Watkins, G.T. (1998) Elevation and the distribution of salt-marsh Foraminifera, St. Catherines Island, Georgia; a taphonomic approach, *Palaios*, 13, (6), p570-580.

Hayward, B.W. and Hollis, C.J. 1994. Brackish foraminifera in New Zealand: A taxonomic and exologic review. *Micropaleontology* 40: 185-222

Hayward, B.W., Scott, G.H., Grenfell, H.R.m Carter, R., Lipps, J.H., 2004. Techniques for estimation of tidal elevation and confinement (~salinity) histories of sheltered harbours and estuaries using benthic foraminifera: examples from New Zealand. *The Holocene* 14: 218-232

Hayworth, A. and Kidson, C. 1982: Sea-level changes in southwest England and Wales. *Proceedings of the Geologists' Association* 93: 91-112

Horton, B.P. 1999. The distribution of contemporary intertidal foraminifera at Cowpen Marsh, Tees Estuary, UK: implications for studies of Holocene sea-level changes. *Paleogeography, paleoclimatology, paleoecology*. 149 (1-4): 127-149

IPCC. 2007b. In: R.K. Pachauri and A. Reisinger, Editors, *Climate Change 2007: Synthesis Report. Core Writing Team*, Cambridge University Press, Cambridge (2007).

Jennings, A.E. and Nelson, A.R. 1992. Foraminiferal assemblage zones in Oregon tidal marshes – relation to marsh floral zones and sea-level. *Journal of Foraminiferal Research*. 22: 13-29

Jennings, A.E., Nelson, A.R., Scott, D.B. and Arevena, J.C. 1995. Marsh foraminifera assemblages in the Valdiva estuary, south-central Chile, relative to vascular plants and sea level. *Journal of Coastal Research*. 11: 107-123

Jennings, A.E., Weiner, N.J., Helgadottir, G. and Andrews, T. 2004. Modern foraminiferal faunas of the southwestern to northern Iceland shelf: oceanographic and environmental controls. *Journal of Foraminiferal Research*. 24: 180-207

Jonasson, K.E. and Patterson, R.T. 1992. Preservation potential of salt marsh foraminifera for Fraser river delta, British Columbia. *Micropaleontology*. 38: 289-301

Juggings, S. 2003. C² version 1.4: software for ecological and paleoecological data analysis and visualization: department of geography, Newcastle Upon Tyne, UK. 69.

Kemp, A.C., Horton, B.P., Corbett, D.R., Culver, S.J., Edwards, R.J., van de Plassche, O., 2009. The relative utility of foraminifera and diatoms for reconstructing late Holocene sea-level change in North Carolina, USA. *Quaternary Research* 71, 9–21.

Kent, M., and P. Coker. 1992. Vegetation description and analysis: a practical approach. Belhaven Press, London

Maddy, D. & Brew, J.S. 1995. Statistical modelling of Quaternary science data. Technical Guide 5. Quaternary Research Association, Cambridge.

- Massey, A.C., Gehrels, W.R., Charman, D.J. and White, S.V. 2006. An intertidal foraminifera-based transfer function for reconstructing Holocene sea-level change in southwest England. *Journal of Foraminiferal Research*. 36 (3): 215-232
- Matera, N.J. and Lee, J.J. 1972. Environmental factors affecting the standing crop of foraminifera in sublittoral and pasammolittoral communities of a Long Island salt marsh. *Marine Biology*, 14: 89-103
- Murray, J.W. 1971 Living foraminiferids of tidal marshes: a review. *Journal of Foraminiferal Research* 1: 153-161
- Murray, J.W. 1983. Population dynamics of benthic foraminifera: results from the Exe estuary, England. *Journal of Foraminiferal Research*. 13: 1-12
- Murray, J.W. 1986. Living and dead Holocene foraminifera of Lyme Bay, southern England. *Journal of Foraminiferal Research*. 16: 347-352
- Murray, J.W. 1991. Ecology and paleoecology of benthic foraminifera. Harlow: Longman.
- Murray, J.W. 2000a. The enigma of the continued use of total assemblages in ecological studies of benthic foraminifera. *Journal of Foraminiferal Research*. 30: 244-245; 2002, *ibid.*, 32: 200; 2002 (erratum).
- Murray, J.W. 2002. Monitoring in coastal environments using foraminifera and thecamoebian indicators, D.B. Scott, F.S. Medioli, C.T. Schfer. Cambridge University Press, Cambridge, 2001, pp177
- Murray, J.W. 2003a. Patterns in the cumulative increase in species from foraminiferal time-series. *Marine Micropaleontology*. 48: 1-21
- Murray, J.W. 2006. Ecology and Applications of Benthic Foraminifera. Cambridge University Press. New York.
- Murray, J.W., Weston, J.F. and Sturrock, S. 1983. Sedimentary indicators of water movement in the western approaches to the English Channel. *Continental Shelf Research*. 1: 339-352
- Murray, J.W., Alve, E. and Cundy, A. 2003. The origin of modern agglutinated foraminiferal assemblages: evidence from a stratified fjord. *Estuarine, Coastal and Shelf Science*. 58: 677-
- Patterson, R.T. 1990. Intertidal benthic foraminifera biofacies on the Fraser River Delta, British Columbia. *Micropaleontology*. 36: 229-244
- Patterson, R.T., Guilbault, J.P. and Thomson, R.E. 2000. Oxygen level control on foraminiferal distribution in Effingham Inlet, Vancouver Island, British Columbia, Canada. *Journal of Foraminiferal Research* 30: 321-335
- Phelger, F.B. 1970. Foraminiferal populations and marine marsh processes. *Limnology Oceanography* 15: 522-534
- Phelger, F.B. 1977. Soils of marine marshes, in wet coastal ecosystems. Elsevier, Amsterdam, pp. 69-77

Phelger, F.B. and Walton, W.R. 1950. Ecology of marsh and bay foraminifera, Barnstable, Massachusetts. *American Journal of Science*. 248: 274-294

Rodwell, J.S. 2000. British plant communities, maritime communities and vegetation of open habitats. Cambridge University Press, Cambridge, UK

Saffert, H. and Thomas, E. 1998. Living foraminifera and total populations in salt marsh peat cores: Kelsey marsh (Clinton, CT) and the Great Marshes (Barnstable, MA). *Marine Micropaleontology*. 33: 175-202

Schroder, C.J., Scott, D. B. and Medioli, F.S., Bernstein, B.B. and Hessler, R.R. 1988. Larger agglutinated foraminifera: comparisons of assemblages from central North Pacific and western North Atlantic (Nares Abyssal Plain). *Journal of Foraminiferal Research*. 18: 25-41

Scott, D.B. 1976b. Quantitative studies of marsh foraminiferal patterns in southern California and their application to Holocene stratigraphical problems. *Maritime Sediments, Special Publication*. 1: 153-170

Scott, D.B., Medioli, F.S. and Schafer, C.T. 2001. Monitoring in coastal environments using foraminifera and thecamoebian indicators. Cambridge University Press, Cambridge, UK

Scott, D.B. and Medioli, F.S. 1980a. Living vs. total foraminiferal populations; their relative usefulness in palaeoecology. *Journal of Paleontology*. 54: 814-831

Scott, D.B. and Medioli, F.S. 1980b. Quantitative studies of marsh foraminiferal distribution in Nova Scotia: implications for sea level studies. *Contributions from the Cushman Foundation for Foraminiferal Research, Special Publication*. 17: 1-58

Scott, D.B. and Medioli, F.S. 1986. Foraminifera as sea-level indicators. In: O. Van de Plassche, Editor, Sea-level research: A manual for the collection and evaluation of data, Geo books, Norwich, 435-456

Scott, D.B., Collins, E.S., Duggan, J., Asioli, A., Saito, T., Hasegawa, S., 1996. Pacific Rim marsh foraminiferal distributions: implications for sea-level studies. *Journal of Coastal Research* 12: 850-861

Scott, D.B., Medioli, F.S., Schafer, C.T., 2001. Monitoring in coastal environments using foraminifera and thecamoebian indicators. Cambridge University Press, Cambridge

Sen Gupta, B.K. 1999. Modern foraminifera. Dordrecht: Kluwer.

Shennan, I., Milne, G. and Bradley, S. 2009. Late Holocene relative land- and sea-level changes: Providing information for stakeholders. *GSA Today*. 19 (9): doi: 10.1130

Shennan, I. and Horton, B. 2002. 'Holocene land- and sea-level changes in Great Britain.', *Journal of quaternary science*., 17 (5-6). pp. 511-526

Shennan, I., Rutherford, M.M., Innes, J.B., Walker, K.J., 1996. Late glacial sea level and ocean margin environmental changes interpreted from biostratigraphic and

lithostratigraphic studies of isolation basins in northwest Scotland. *Geol. Soc.* 111: 229-244

Shennan, I., Long, A.J., Rutherford, M.M, Innes, J.B., Green, F.M. and Walker, K.J. 1998 Tidal marsh stratigraphy, sea-level change and large earthquakes-II: submergence events during the last 3500 years at netarts Bay, Oregon, USA. *Quaternary Science Reviews*. 17 (4-5): 365-393

Shennan, I., Scott, D.B., Rutherford, M., & Zong, Y.Q. 1999. Microfossil analysis of sediments representing the 1964 earthquake, exposed at Girdwood Flats, Alaska, USA. *Quaternary International* 60: 55-73.

Shennan, I., Peltier, W.R., Drummond, R., Horton, B., 2002. Global to local scale parameters determining relative sea level changes and the post-glacial isostatic adjustment of Great Britain. *Quat. Sci. Rev.* 21, 397– 408.

Summerfield, 1991 M.A. Summerfield, *Global Geomorphology. An introduction to the study of landforms*, Longman Scientific & Technical, Boston

Teal, J.M. 1996. Salt marshes: They offer diversity of habitats. *Oceanus* 39: 13-160

Telford, R.J. and Birks, B. 2005. The secret assumption of transfer functions: problems with spatial autocorrelation in evaluating model performance. *Quaternary Science Reviews*. 24: 2173-2179

Vickerman, K. 1992. The diversity and ecological significance of Protozoa. *Biodiversity and Conservation* 1: 334–341

Walton, W.R. 1952. Techniques for recognition of living foraminifera. *Contrib. Cushman Found. Foraminiferal Res.* 3, 56-60

Woodroffe, S.A. and Horton, B.P. 2005. Holocene sea-level changes in the Indo-Pacific. *Journal of Asian Earth Sciences*. 25 (1): 29-43

Zong, Y. 1998. Diatom records and sedimentary responses to sea-level changes during the last 8000 years in Roudsea Wood, North-West England. *The Holocene* 8(2): 219-228.

Zong, Y. & Horton, B. 1999. Diatom-based tidal level transfer function and its applications to palaeo-sea-level reconstruction. *Journal of Quaternary Science* 14(2): 153-167.